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# Choice of the Optimal Configuration of Modular Reusable Fixtures

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**Abstract**—Multicriteria choice of the optimal fixture configuration from a set of competing options is considered. An approach is developed for automated formulation of those options on the basis of a library of functional elements and the system of functional elements of modular reusable fixtures.

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Fixtures for locating and clamping workpieces in metal-cutting machine tools have a considerable influence on their efficiency and performance.

The structure of the fixture is hierarchical and consists of four levels that differ in the number of components and the degree of generalization (Fig. 1). The relations between the components at each level depend on the combination of the structural units at lower levels into higher-level structural units. Each structural element is characterized by the shape, dimensions, and function specified by the designer. The part consists of a set of structural elements, which are combined to form the specified function.

A functional module is an independent part of the fixture which consists of components and/or assemblies with a common function. For example, the locating module for locating of a stepped shaft in drilling and milling machines consists of changeable setups that ensure locating of the workpiece at the external cylindrical surfaces, as well as a stay that positions the end of the shaft (that is, a resting base). Thus, all the components of the locating module have a shared function: locating of the workpiece in the fixture.

The best fixture configuration is selected by multicriteria optimization, with the formation of competing options (Fig. 2).

On the basis of initial data from the working drawing and operational sketch of the part to be machined and also from the technological documentation and design specifications for the fixture, we may determine the functional elements required for locating of the workpiece, taking into account the production conditions. Possible designs of the fixture components may be found in the library of functional elements (Fig. 3).

The library consists of groups of elements that perform the same functions within the fixture. For example, supporting elements include base plates and angle brackets; locating elements include supporting plates, supports, V-blocks, and pins; auxiliary locating elements include self-stabilizing and adjustable supports; and clamping elements include various bars, levers, clamps, and so on.

The design process involves the selection of standard options determined by some set of parameters or conditions. As a rule, complex logical relations will exist between the conditions and solutions. Tabular methods are used for clear and compact representation of the data. Such methods reduce the time required for formulation of the problem, programming, and debugging. Most commonly, tables of solutions are employed, with the following benefits for automated design: the tables are relatively simple to compile; they may readily be checked for completeness, consistency, and redundancy of the information; and they permit modification of the data and the introduction of additional parameters.

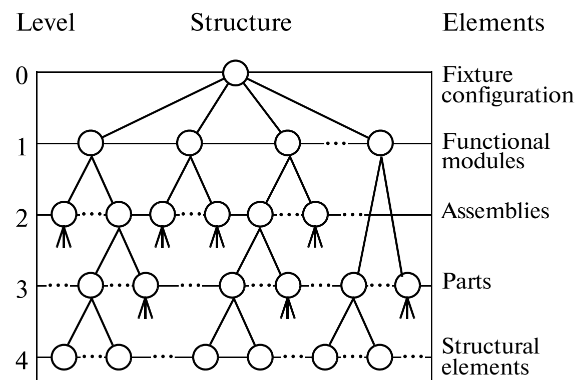


**Fig. 1.** Hierarchical structure of fixture.

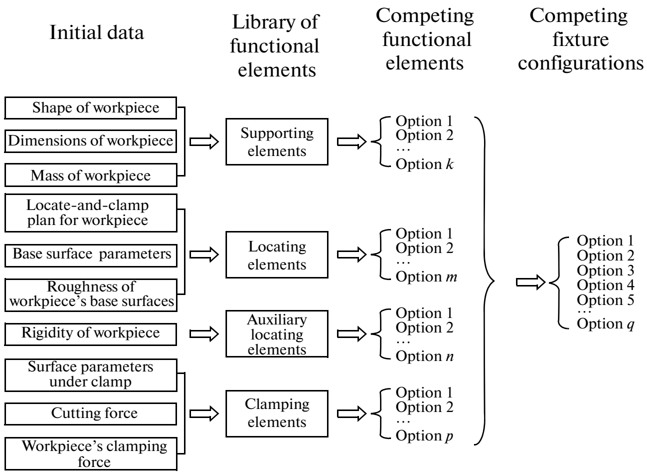


**Fig. 2.** Generation of competing options.

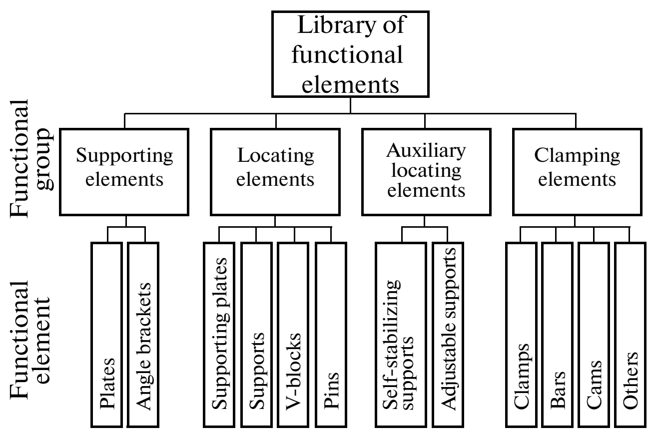


**Fig. 3.** Structure of the library of functional elements.

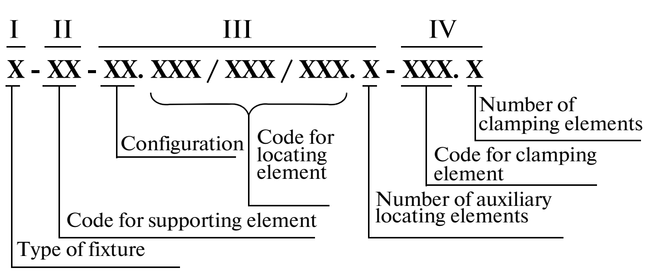


**Fig. 4.** Structural formula of fixture configuration.

The library of functional elements is based on tables of solutions for each group of functional elements: supporting elements, locating elements, auxiliary locating elements, and clamping elements. The supports differ in the type of head, the maximum load, the possible height adjustment, the degree of automation of adjustment, and their function, depending on the quality of the workpiece's base surfaces. V-blocks and pins are selected in accordance with the state of the workpiece's base surfaces, the diameters of the base surfaces, and the method and degree of automation of adjustment. The clamping elements are selected in accordance with the degree of automation of adjustment, the range of regulation, the minimum and maximum heights of the workpiece, and the maximum clamping force.

Thus, each group of functional elements contains structures with a single function that differ in their engineering parameters and hence have a particular range of applications. For purposes of identification, each element in the library is assigned a code.

On the basis of the initial data and the engineering parameters of the functional elements, we may select some number of competing options for each group. The number of competing options will be different for different groups. Thus, in the general case, we may identify $k$ options in terms of supporting elements, $m$ options in terms of locating elements, $n$ options in terms of auxiliary locating elements, and $p$ options in terms of clamping elements.

On the basis of the individual elements selected, we may create a set of competing options for the fixture. The total number of such options will be equal to the product of the numbers of options for each group: $q = kmnp$.

Any fixture configuration may be expressed as a structural formula, consisting of alphanumeric code, in which four groups (I–IV) are separated by hyphens (Fig. 4).

Group I determines the type of fixture and corresponds to the work performed. For example, D, M, and DM denote clamps in drilling, milling, and drilling and milling machine tools, respectively. Group II presents the code for the supporting element, from the library of functional elements. Group III characterizes the locating module. It includes code for the workpiece and fixture configuration, followed by the codes for the basic locating elements implementing the theoretical locate-and-clamp plan. (The codes for different positional elements are separated by a forward slash.) Depending on the basing plan, the number of different locating elements used in the fixture configuration may be 1–3. With less than three positional elements, a zero appears in the fields with no codes. Finally, in group III, the number of auxiliary locating elements required to ensure the required workpiece rigidity is presented. Group IV provides information regarding the clamping elements, including the number used.

Multicriteria optimization requires the development of a system of competing options, but manual generation of such a set is extremely time-consuming. Accordingly, this process is automated, on the basis of the algorithmic structure of the system for selecting optimal fixture configurations (Fig. 5). This system consists of a database and three modules: the initial-data module; the information retrieval module; and the computational module.

Many factors affect the choice of the fixture configuration. Structural factors include the shape, size, mass, and rigidity of the parts. Technological factors include the operations to be performed, the type of metal-cutting tools and equipment, and the locate-and-clamp plan for the workpieces. Production factors include the type of production and the annual targets for batch outputs. Economic, ergonomic, and esthetic considerations are also important.

The basic functions of databases are the accumulation, improvement, storage, and provision of information regarding existing developments, in accordance with the requirements arising from the equipment used. The database in the system for automated synthesis of fixture configurations includes libraries of functional elements, standard information, and information regarding metal-cutting tools and equipment.

The library of standard information includes tables of tolerances and fitting data; accuracy and surface-roughness data; standards regarding the machining time and the time for setup and modification of the fixture configurations; and cutting conditions.

The library relating to metal-cutting tools and equipment includes the characteristics of metal-cutting equipment, especially for the working zone and the sites where clamping attachments are installed. For drilling and milling machine tools, for example, we need the following data: the dimensions of the working table; the distance between the slots in the table; and the distance from the end of the spindle to the table in the topmost position. In addition, the library includes manufacturers' recommendations regarding tool selection for particular machining conditions.

The complexity of manufacturing processes is due to the great diversity of fixture configurations and the strict requirements that they must satisfy.

The traditional sequence in which the fixture configuration is developed is as follows: choice of the base plate; choice of the locating elements; choice of the auxiliary locating elements; and choice of the clamping elements. Different factors come into play for the choice of each element. Thus, choice of the base plate requires data regarding the workpiece's shape, size and mass and the material from which it is made. The initial information for the selection of the locating elements relates to the shape of the workpiece, the type of base surfaces, and their quality. To ensure additional rigidity and stability of the workpiece, auxiliary locating elements may be used. Choice of the clamping elements is based on the characteristics of the machined surfaces and the surfaces under the clamp, as well as data regarding the load on the workpiece (the cutting forces and the clamping forces).

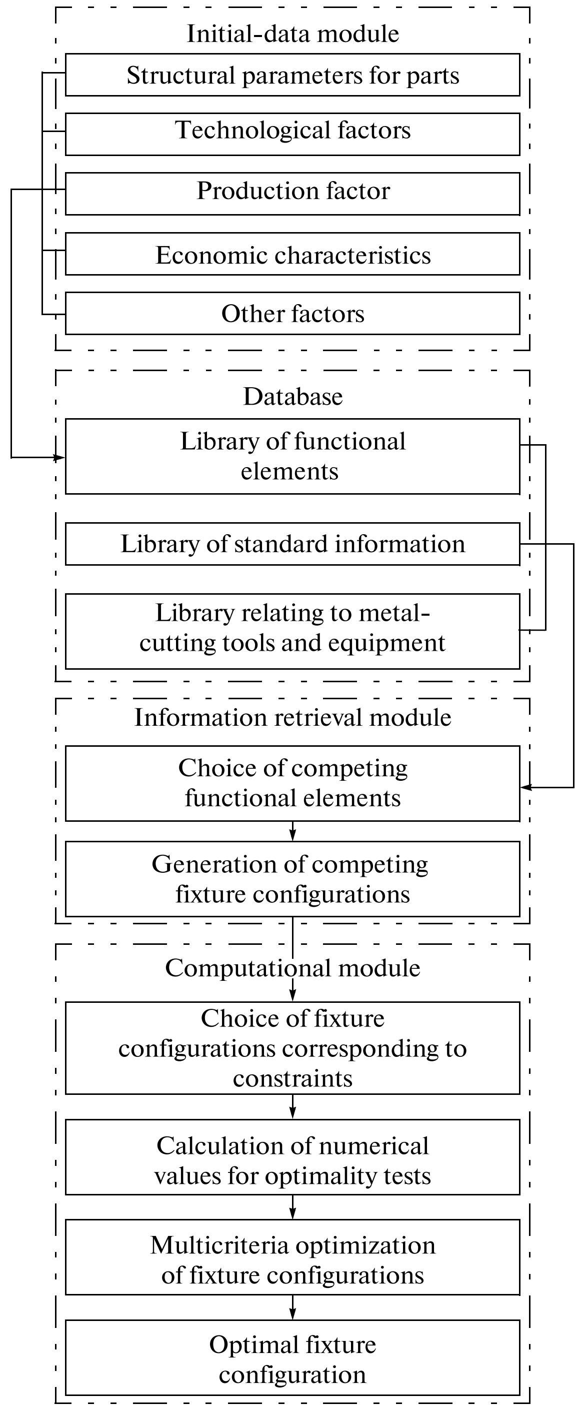


**Fig. 5.** Algorithmic structure of system for the synthesis of fixture configurations.

To increase locating accuracy of the elements at the base plate and with respect to one another, gap-free locating is proposed for the components of the modular reusable fixtures [1]. To this end, a self-centering unitized bush has been developed, so as to reduce the

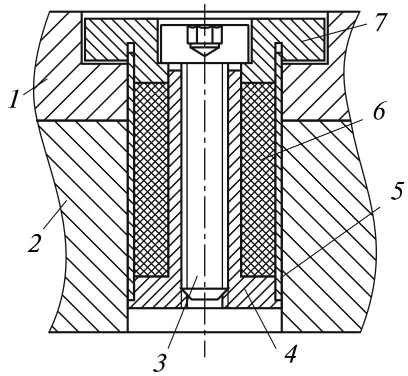


**Fig. 6.** Self-centering composite bush for gap-free basing of the clamping attachment's components.

assembly time [2]. For locating and clamping of element *1*, it is placed on base plate *2*, so that their base holes are aligned; self-centering unitized bushes are inserted in those holes. Then screw *3* (Fig. 6) is tightened in the threaded hole of body *4*, so that lid *7* compresses hydroplastic mass *6*. Under the action of that mass, which presses uniformly on the internal surface of thin-walled steel shell *5*, the shell is deformed. As a result, the element of the fixture is centered and clamped to the base plate.

The self-centering unitized bush enhances the locating accuracy of the fixtures' components and hence reduces its influence on the locating error of the workpiece. In addition, this bush may be used for locating of workpieces with respect to a plane and two holes or with respect to two planes and a hole. This improves tool access in contour machining, for example, and hence improves the drilling and milling efficiency.

To improve the efficiency of machine tools in flexible production, we have developed a system of functional elements that ensures high flexibility and rapid adjustment of the locating elements and clamping elements over a broad dimensional range. This minimizes the loss of time in readjusting for different products. The proposed locating modules are applicable to the basic locate-and-clamp plans for plane parts, case-shaped parts, and rotary parts.

To improve the locating accuracy at plane surfaces, an adjustable support with a basic scale and a vernier scale has been proposed [3]. This permits adjustment of the support's position within 0.1 mm (version 1) or 0.05 mm (version 2), with considerable time savings.

Plane locating of workpieces is provided by the reusable locating module proposed in [4]. The position of the supports may be automatically adjusted by means of a screw mechanism.

A changeable plate was proposed for the locating of workpieces with respect to a plane and two holes in [5]. This system ensures tool access in contour machining.

An adjustable support was proposed for the locating of workpieces with respect to the inclined end surface in [6]. This system permits vertical and horizontal adjustment of the support's position.

An adjustable V-block increases the basing precision of cylindrical blanks thanks to the simultaneous motion of the supports using a screw mechanism [7]. The necessary position of the supports for workpieces of particular diameter is monitored by means of scales applied to the supports that correspond to the base-surface diameter for workpieces of the given batch.

A self-centering three-cam chuck has been proposed for the locating of rigid disks or short shafts [8]. A screw mechanisms permits adjustment of the cams toward or away from the center of the body, by the required base surface diameter.

Workpieces with large axial holes may be mounted on an expanding mandrel, which permits locating with a wide range of hole diameters [9]. The T junction of the pistons with the wedge permits reliable clamping of the workpiece and free pulling-out of the machined part.

For the clamping of workpieces with very nonplanar base surfaces, changeable vise jaws have been developed [10]. The workpieces are based by means of four rigidly fixed supports and sixteen self-stabilizing supports within body holes.

A clamping module that permits automated clamping and unfixturing of the workpieces by means of a gear–rack mechanism and a rotary clamp was proposed in [11]. This system permits the unobstructed pulling-out of the machined parts and insertion of new workpieces.

The choice of the best fixture configuration is a multicriterial problem. In other words, it carries out a system of target functions. In multicriteria optimization, the best solution with respect to all the criteria is impossible. Therefore, it is expedient to realize a sequential approach [12]. In considering discrete systems that consist of individual objects corresponding to a set of criteria, we may reasonably assign increments to each criterion, with known characteristics of the fixture configurations. In selecting the optimal fixture configuration by a sequential approach, the identification of the steps is not subjective, since they will be selected as objective characteristics of each competing fixture configuration. According to the adopted methodology, the optimization criteria are first determined. Then the criteria are analyzed and ranked in importance: the first is the most important, and the last is the least important. We adopt the following criteria in optimizing the fixture configuration: the workpiece's locating error $\varepsilon_s \longrightarrow$ min; the flexibility of the clamping attachment $G_F \longrightarrow$ max; the cost $C_F \longrightarrow$ min; and the metal content $M_F \longrightarrow$ min.

The constraints on the choice of the optimal fixture configuration are as follows:

(1) the setting error must be within the tolerance: $\varepsilon_s \le [\varepsilon_s]$;

(2) the flexibility of the fixture must be consistent with the production requirements: $G_F \ge [G_F]$;

(3) the steel intensity of the fixture must be less than the load capacity of the machine tool's table: $M_F < \Gamma_{ta}$.

The mathematical model of multicriterial synthesis of the fixture configuration takes the form

$$\begin{cases} \varepsilon_s = \sqrt{\varepsilon_l^2 + \varepsilon_c^2 + \varepsilon_{man}^2 + \varepsilon_{l.m}^2 + \varepsilon_{we}^2} \longrightarrow \min; \\ G_F = \left(1 - \dfrac{1}{n}\right) \dfrac{1}{1 + \sum\limits_{i=1}^{n} t_{s_i} / \sum\limits_{i=1}^{n} t_i N_i} \longrightarrow \max; \\ C_F = \sum\limits_{a=1}^{b} C_{dea}^{h} \underline{t_{dea}} + \sum\limits_{q=1}^{r} k_q \left( C_{maq} + \sum\limits_{j=1}^{m} C_{jq} t_{jq} \right) \\ \qquad + \sum\limits_{e=1}^{d} C_e f_e + C_{as}^{h} t_{as} + C_{ov} \longrightarrow \min; \\ M_F = \sum\limits_{k=1}^{p} m_k + m_w \longrightarrow \min; \end{cases}$$

$$\varepsilon_p \le [\varepsilon_p];$$

$$G_{CA} \ge [G_{CA}];$$

$$M_{CA} < [\Gamma_{ta}],$$

where $\varepsilon_l$ and $\varepsilon_c$ are the locating and clamping errors of the blank; $\varepsilon_{man}$ is the manufacturing error of the clamping attachment's components; $\varepsilon_{l.m}$ is the locating error of the fixture in the machine tool; $\varepsilon_{we}$ is the error due to wear of the locating elements; $n$ is the number of types of parts machined in the fixture; $t_s$ is the setup time before machining a part of type $i$; $t_i$ is the machining time for the part of type $i$; $N_i$ is the number of part of type $i$ in the production batch; $C_{dea}^{h}$ is the hourly pay of the designer in designing part $a$; $t_{dea}$ is the time consumed in the design of part $a$; $b$ is the number of parts for the fixture; $k_q$ is the size of the manufacturing batch for part $q$; $r$ is the upper limit on $q$; $C_{maq}$ is the cost of the material in manufacturing a single exemplar of part $q$; $C_{jq}$ is the cost of operation $j$ per unit time, in manufacturing part $q$; $t_{jq}$ is the time for operation $j$ in manufacturing part $q$; $m$ is the number of machining operations for part $q$; $C_e$ is the purchase cost of part $e$; $f_e$ is the size of the purchased batch of part $e$; $d$ is the upper limit on $e$; $C_{as}^{h}$ is the hourly wage of the assembly worker; $t_{as}$ is the time required for assembly of the fixture; $C_{ov}$ is the overhead; $m_k$ is the mass of part $k$ in the fixture; $p$ is the number of parts in the fixture; $m_w$ is the mass of the workpiece.

In the sequential approach, multicriteria optimization takes the following form: determination of the optimal value with respect to the first criterion; specification of an increment for the first criterion and determination of the optimal value with respect to the second criterion; and so on. In that case, the system of optimization problems takes the form

$$K_1 = \inf \varepsilon_s(u);$$

$$K_2 = \sup G_F(u), \text{ when } \varepsilon_s \le K_1 + \Delta\varepsilon_s;$$

$$K_3 = \inf C_F(u), \text{ when } G_F(u) \ge K_2 - \Delta G_F;$$

$$K_4 = \inf M_F(u), \text{ when } C_F(u) \le K_3 + \Delta C_F,$$

where $u$ is an option from the set $U$ of fixture configurations; $\Delta\varepsilon_s$, $\Delta G_F$, and $\Delta C_F$ are increments determined in pairwise and successive comparisons.

The result of multicriteria optimization will not be optimal in terms of all the local criteria but will be the best overall in terms of all the characteristics.

As an example, consider the synthesis of fixture configurations for the locating of shafts on drilling and milling machine tools. The competing options are formulated on the basis of the initial data and the library of functional elements (Fig. 7). For locating of the workpiece with respect to two external cylindrical surfaces and the end, we select six types of V-blocks (codes 310 and 304–308) and two laterals supports (codes 253 and 255) from the library of functional elements. The workpiece may be clamped by means of five clamping elements (codes 201, 202, 206, 237, and 238), and two base plates are selected (codes 22 and 31).

On the basis of various combinations of these functional elements, we generate sets of competing options; the total number of competing fixture configurations is the product of the numbers of possible options for each group. In the present case, the number of fixture configurations that differ in precision, flexibility, cost, and steel intensity is 120.

In accordance with the algorithmic structure for the synthesis of fixture configurations (Fig. 5), we select the options that satisfy the constraints on the model.

The permissible setting error $[\varepsilon_s]$ is assumed to be $[\varepsilon_s] = 0.7Td$, where 0.7 is a factor corresponding to semifinishing of surfaces [13]; $Td$ is the tolerance on the executed dimensions. (For the calculations, we assume that $Td = 0.16$ mm; this corresponds to machining in precision class $IT11$.) Thus, options that ensure setting error no greater than $[\varepsilon_s] = 0.112$ mm meet the accuracy requirements.

To ensure high flexibility, we require that $0.25 \le G_F < 1$ [14]. Thus, the selected options must be such that $G_F \ge 0.25$.

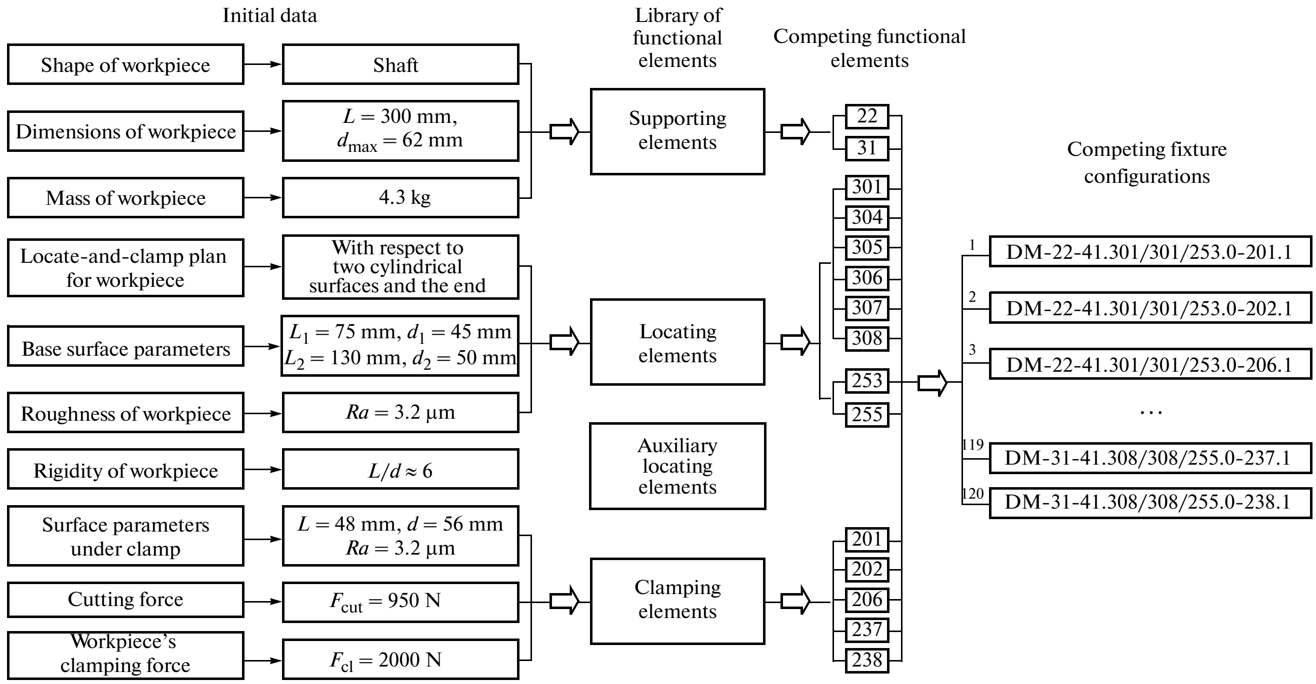


**Fig. 7.** Generating of the competing fixture configurations in shaft locating.

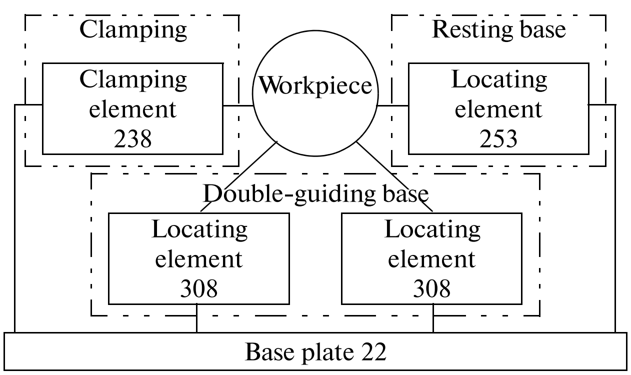


**Fig. 8.** Graphical model of optimal fixture configuration.

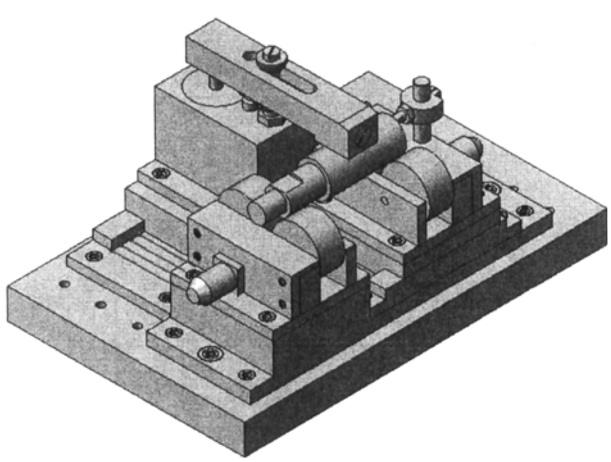

**Fig. 9.** Locating of stepped shaft in drilling and milling machine.

The steel intensity of the fixture must be less than the load capacity of the machine tool's table, which is 200 kg according to the characteristics. Thus, we require that $M_F < 200$ kg.

As a result of multicriteria optimization, taking into account that the tolerance $Td = 0.16$ mm and the number of parts in the batch is $N = 10$, we find that best fixture configuration is described by the structural formula DM-22-41.308/308/253.0-238.1. It consists of a base plate (code 22), two V-blocks (code 308), a lateral support (code 253), and a clamp (code 238), with the characteristics $\varepsilon_s = 0.07$ mm; $G_F = 0.67$; $C_F = 2345$ USD; and $M_F = 68.5$ kg. The optimal clamping-attachment configuration in the given conditions is shown graphically in Fig. 8. Its practical application is illustrated in Fig. 9 [15].

## CONCLUSIONS

(1) A multicriteria optimization system has been developed by analysis of the hierarchical structure of the fixture configuration, taking into account the characteristics of the components and the production conditions. This system permits the choice of the best fixture configuration from a set of competing options.

(2) We have developed an approach to the automated generation of a set of competing options on the basis of a library of functional elements, taking account of the workpiece's characteristics and production conditions.

(3) A database of functional elements of fixtures has been developed on the basis of tables of solutions,

which take account of structural characteristics and indicate effective applications of the designs.

## REFERENCES


1. Karpus, V.E. and Ivanov, V.A., Modular Reusable Fixtures *Vestn. Mashinostr.*, 2008, no. 11, pp. 46–50.
2. Ukrainian Patent on Useful Model 44718.
3. Ukrainian Patent on Useful Model 31000.
4. Ukrainian Patent on Useful Model 31469.
5. Ukrainian Patent on Useful Model 34438.
6. Ukrainian Patent on Useful Model 29824.
7. Ukrainian Patent on Useful Model 29823.
8. Ukrainian Patent on Useful Model 31468.
9. Ukrainian Patent on Useful Model 30999.
10. Ukrainian Patent on Useful Model 27551.
11. Ukrainian Patent on Useful Model 38073.
12. Podinovskii, V.V. and Gavrilov, V.M., *Optimizatsiya po posledovatel'no primenyaemym kriteriyam* (Optimization by Successive Criteria), Moscow: Sovetskoe Radio, 1975.
13. Pukhovskii, E.S. and Myasnikov, N.N., *Tekhnologiya gibkogo avtomatizirovannogo proizvodstva* (Flexible Automated Production), Kiev: Tekhnika, 1989.
14. Bondarenko, S.G., *Osnovi tekhnologii mashinobuduvaniya* (Principles of Manufacturing Technology), L'viv: Magnoliya 2006, 2007.
15. Ukrainian Patent on Useful Model 31416.